Title: Multi-INT Signature Collection and Exploitation for Security Los Alamos LDRD Report

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Multi-INT Signature Collection and Exploitation for Security
Los Alamos LDRD Report

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ABSTRACT

This project demonstrates the feasibility of a 2-D passive tracking capability for ground-based and airborne moving sources using multi-INT signal processing of acoustic and seismic signals. We leveraged the recent DDSTE-supported investment in rapid deployable sensors (the Los Alamos Rapid-deployable Sensor Array—LARSA), and used uncrewed aerial vehicles (UAV) as a data source. Moving source types are characterized by their variability with time (exemplified but not limited to the Doppler shift of a passing vehicle) and the signatures used for detection should have similar characteristics. We have demonstrated that time-varying sensor signatures (TVS) combined with time-stable sensor signatures provide a more complete understanding of moving source behavior and drive towards path prediction. Importantly, we have collected a new, relevant LANL dataset of moving sources (small UAV flights and vehicle movement), developed new signatures, and demonstrated a capability to identify, track and forecast the position of TVS.

TECHNICAL GOALS

The project had three primary technical goals: 1) execute a well-planned field experiment to provide data for signature construction and ground truth collection for validation; 2) discover signatures via the mathematical development of features from the acoustic and seismic source signals; and 3) demonstrate a source/target tracking capability with the experimental data. One of the greatest challenges was the mathematical construction of signatures indicative of sources/targets movement. To overcome this difficulty, the team leveraged decades of research experience in underground source location. For fixed sources, a common approach is to identify segments of transient and continuous wave time series that isolate source information. The same approach was taken in this research for moving sources. Acoustic and seismic time series were discretized over time into small segments enabling application of fixed-source analysis methods for each segment.

SCIENTIFIC APPROACH AND RESULTS

The field campaign was executed at LANL (TA-51) to generate and record signatures of interest from time- and distance-varying moving sources. The field experiment used ground-based rapid-deployable seismo-acoustic sensors to detect general operational activities of ground-based and low-altitude airborne vehicles. The UAV flights replicated several relevant airborne flight profiles of interest identified by previous studies [1,2,3] and by stakeholders. We determined ground-based seismic and acoustic sensor deployment locations using an approach from Bayesian design of experiment (DoE) (*Fig 1*) [4,5] to optimize the usefulness of the expected signals from the selected source locations. A suite of target/source locations/paths were identified and used to inform the experimental design. Additionally a three-element acoustic array was designed based on the UAV's expected acoustic signature. This array was deployed near the center of the field area and provided data for traditional array beamforming algorithms to track the motion of the source vehicles.

Using the individual LARSA acoustic sensors (*Fig 2*), combined with the three-element mini arrays, we were able to demonstrate that the UAV could be detected and tracked across all flight profiles (*Figs 3,4*) by breaking up the acoustic signals into one second increments and analyzing the data using traditional beamforming techniques (*Figs 5,6,7*). We also demonstrated an ability to use LARSA's three-component seismometers to detect the point of closest approach (POCA)

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of ground-based vehicles (*Fig 8*) and estimate their average speeds (*Fig 9*). We experienced challenges in the application of a modified Kalman filter approach [6,7,8] that was developed for a track-while-scan (TWS) application to forecast the UAV position, particularly in replicating the type of input data expected from a TWS system (*Fig 10*). This approach, while promising, can provide a basis for forecasting with acoustic measurement inputs, including adapting more complex methods that forecast 3-D position (latitude, longitude, and elevation).

MISSION AGILITY

Algorithms and associated sensing systems for passive detection/identification/tracking are relevant and of high interest to diverse national security and military missions, law enforcement, and facility protection. With the development of mature algorithms, a passive seismo-acoustic tracking system provides a cost-effective option for target detection, identification and tracking. Counter-UAS (cUAS) programs have strong interest in expanded sensing modalities that could help their mission, and this work demonstrates the ability of seismo-acoustic sensors to detect UAV operations. LANL's cUAS program leadership is interested in this project's findings.

TECHNICAL VITALITY

In this project, we have demonstrated (at small scale) the viability of a passive tracking system for a single isolated target, the ability to achieve rapid deployment of inexpensive sensors to achieve robust signature detection, and shown promise in statistical analyses that drive towards forecasting or predicting the location of these moving targets. Additional work could assess the technique's robustness and its application in different environments and settings.

WORKFORCE DEVELOPMENT

The full project report's [9] key contributing authors and main project executors are all junior- to mid-career staff. The lead author and LARSA PI is a research technologist. This project brought together a diverse group of staff who might otherwise not typically collaborate. This work also introduces a new cadre of staff to research aligned with defense mission areas and force protection applications, which we hope will expand LANL capabilities for these customers.

CONCLUSION

Detecting, identifying and tracking a target with active interrogation (e.g. radar) is well established, both in terms of sensing technology and algorithms. However, signals emitted by active interrogation can reveal the interrogator system's location. We demonstrated that propagation of seismic and acoustic waves can be exploited to form a passive interrogation TVS tracking system. In this project, we have demonstrated, at a small scale, the viability of such a system for two isolated targets (UAV and ground vehicles). Algorithms and associated sensing systems for passive detection/identification/tracking are relevant to diverse national security and military missions, law enforcement, and facility protection. Needed seismic and acoustic sensors are inexpensive and with the development of mature algorithms, a passive seismo-acoustic tracking system could provide a cost-effective option for target detection, identification and tracking. Future work on this topic could involve bounding the distances signal could be detected and tracked as well as varying signature sources.
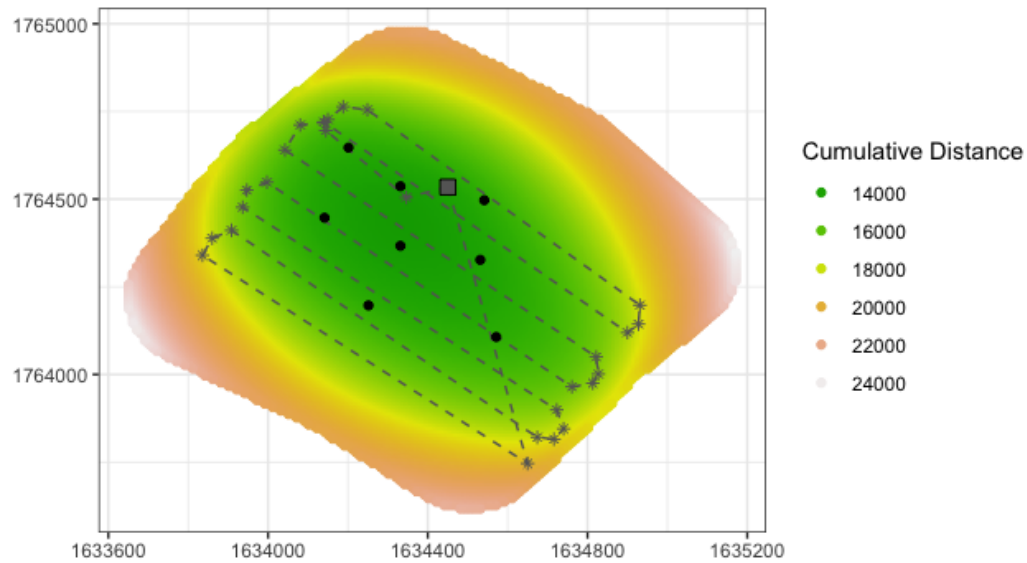
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Figure 1. *Demonstration of optimal sensor deployment. Colored points represent the 13,015 possible sensor locations colored according to the cumulative distance from points of interest on the UAV flight (dashed line). Gray box represents the launch/land site and gray stars indicate the points where the UAV turns a corner, both of which we expect to make a larger acoustic signal. Black circles represent the eight optimal sensor locations.*
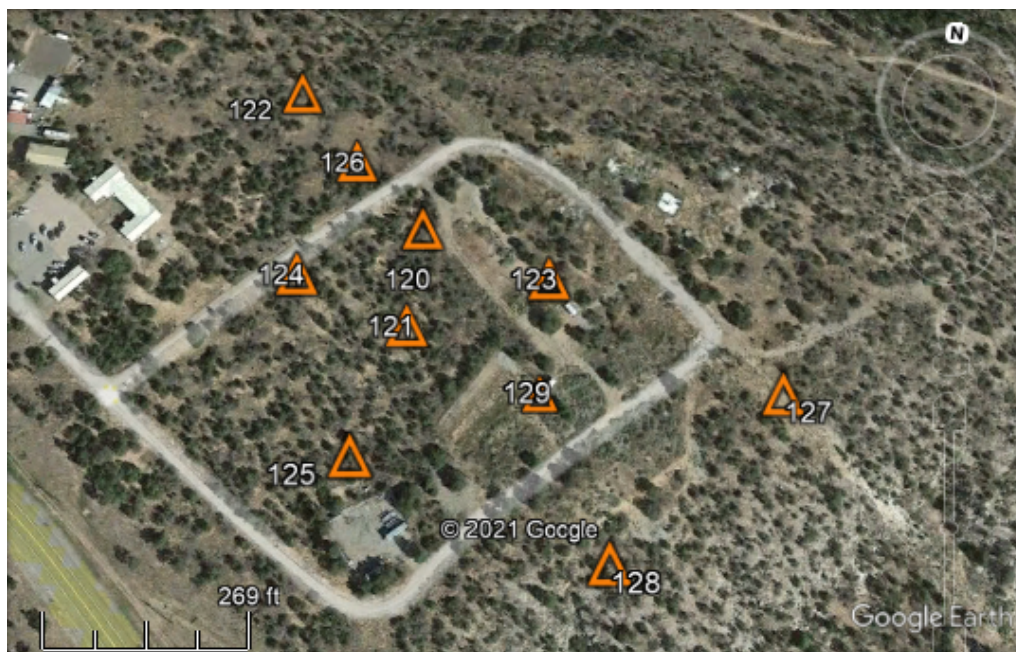

Figure 2. *Image showing the deployed locations of the 10 LARSA stations (orange triangles) at the TA-51 Pinon-Juniper (P-J) plot. The P-J plot is roughly bounded by the rounded rectangular dirt road, Leonard Lane Loop, at the center of the image. Sites 120 and 121 each included a three-element acoustic array.*
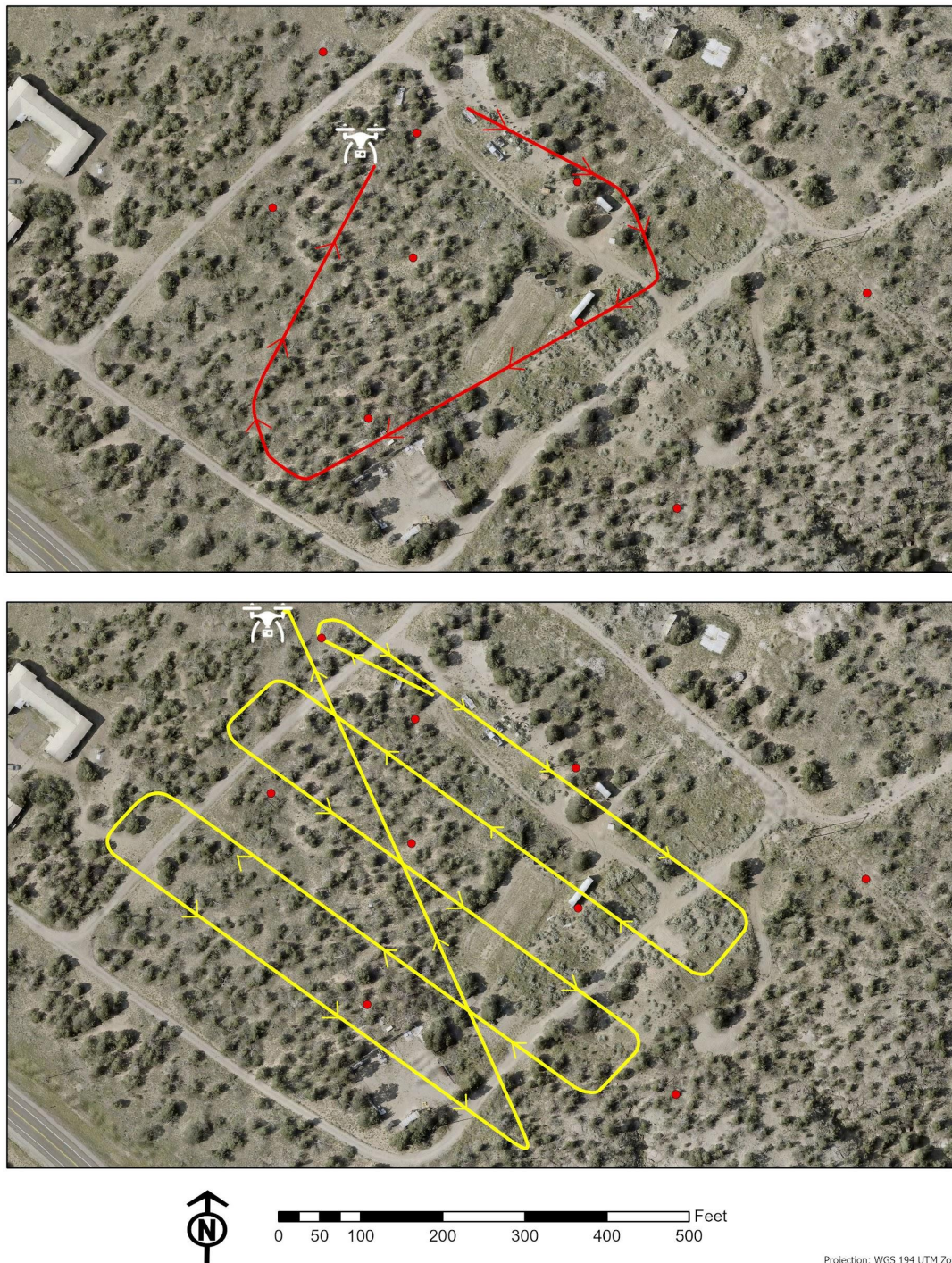
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Figure 3. *Two types of surveillance flight profiles flown by the UAV during the field campaign. (Upper) Perimeter surveillance pattern shown in red. (Lower) Boustrophedonic surveillance pattern shown in yellow. Arrows indicate direction of travel of the UAV from the launch point. Both surveillance flight profiles were flown at 35 m AGL and 50 m AGL over the same path at a forward speed of 3 m/s. Red dots indicate the position of the LARSA sensors as shown in Figure 2.*
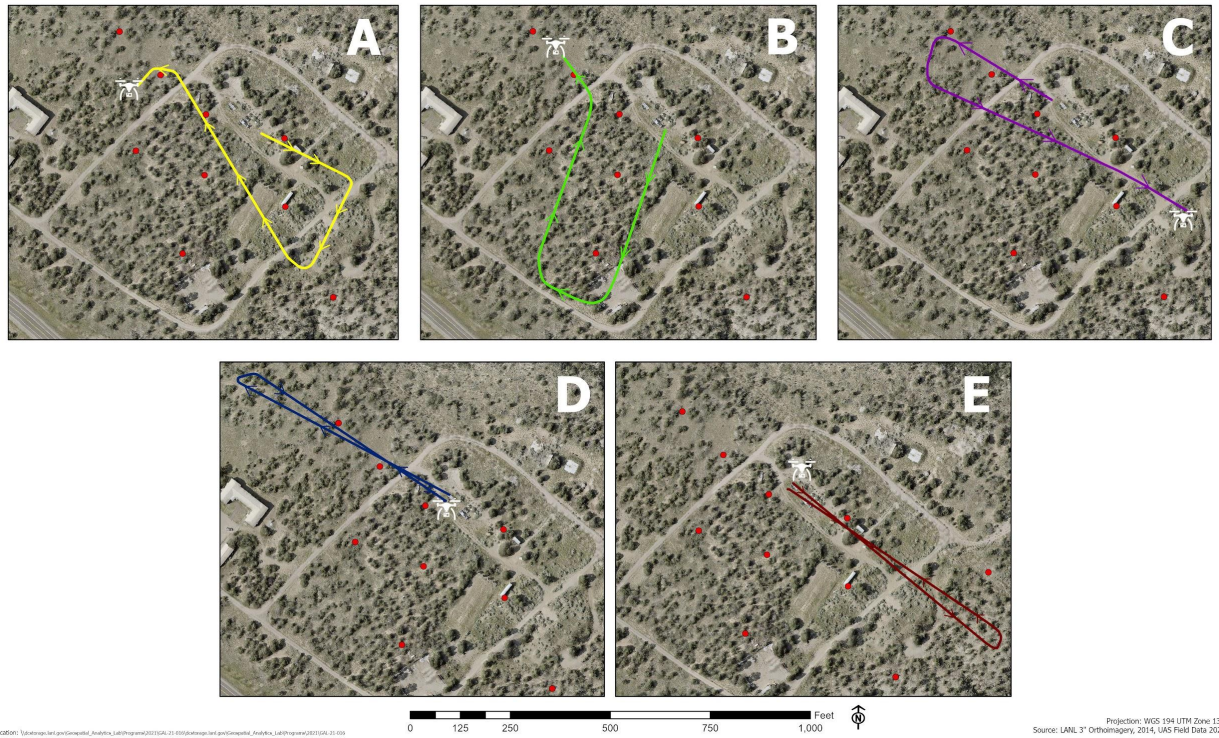
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Figure 4. Maps showing the five threat-oriented flight profiles flown during the campaign. A (yellow), B (green), and C (purple) were designed and flown in an aggressive attack style, while D (blue) and E (red) were designed and flown for exfiltration purposes. See [9] for further discussion on threat mission profiles.
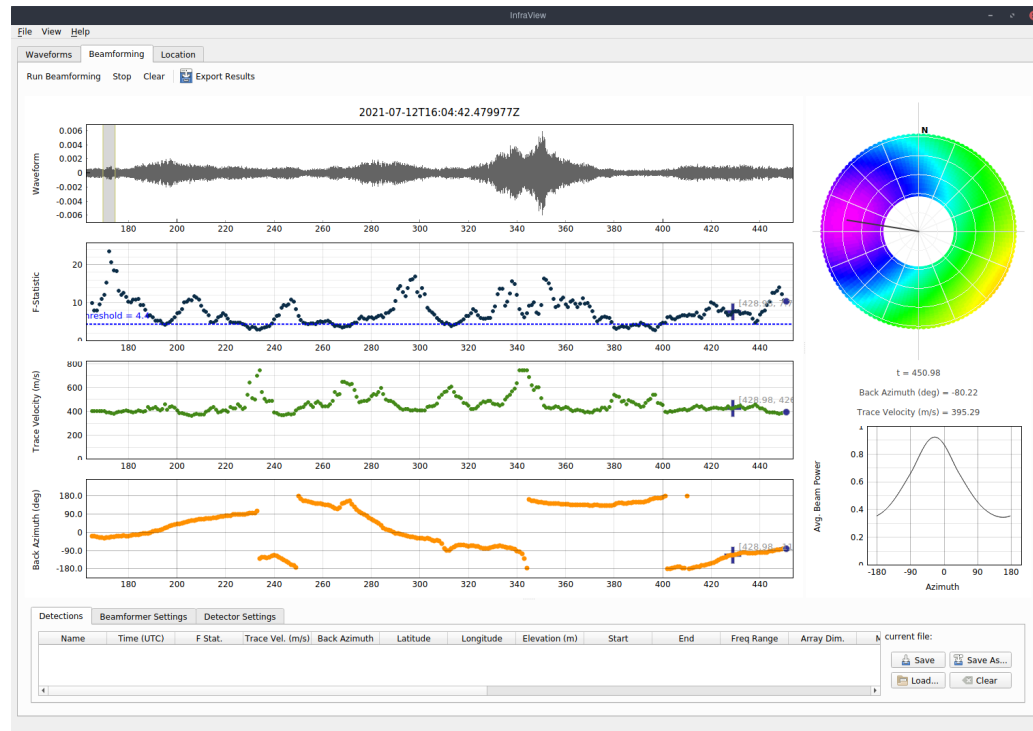
Figure 5. *Screenshot of Infraview, the graphical frontend for infrapy. Infrapy is a python library developed at LANL which is capable of acoustic waveform analysis, beamforming, and source location and association analysis. This image is of the beamforming window with plots showing (from the top): the waveform being analyzed, F-statistics, Trace velocities, and (bottom) the back azimuths for one of the UAV flights.*
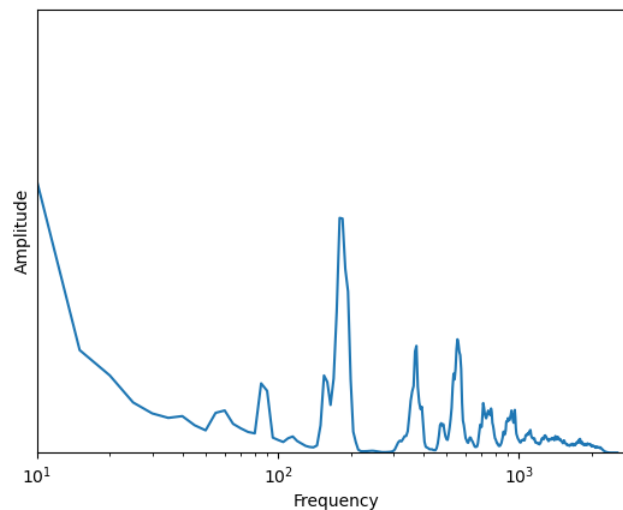

Figure 6. *Plot showing an example of the Power Spectral Density (PSD) of the acoustic signal created by the UAV. The large peak at approximately 180 Hz is the dominant frequency of the UAV and was used to determine that the frequency range used by the beamformer should range from 120 Hz to 240 Hz.*
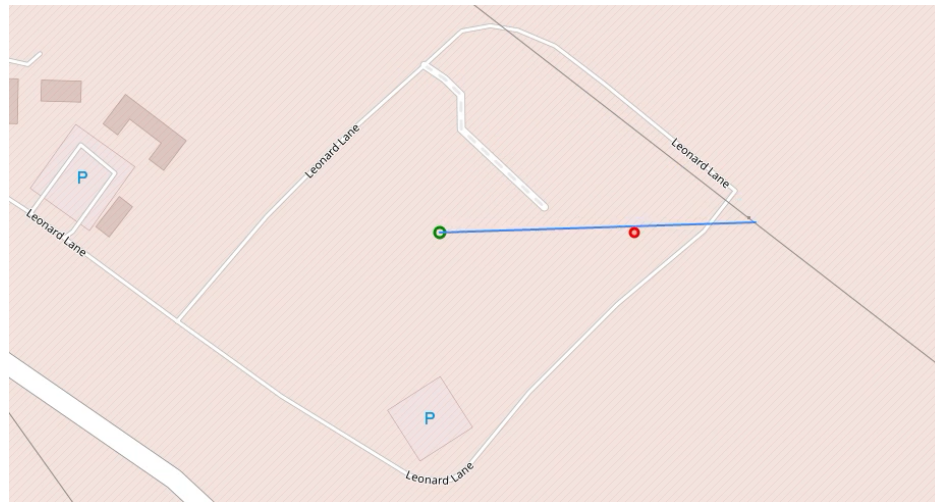
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Figure 7. Example of the UAV (red) and the back azimuth calculated by the beamforming algorithm (blue line) using data from the mini acoustic array at Site 121 (green). Full GIF videos can be found here.
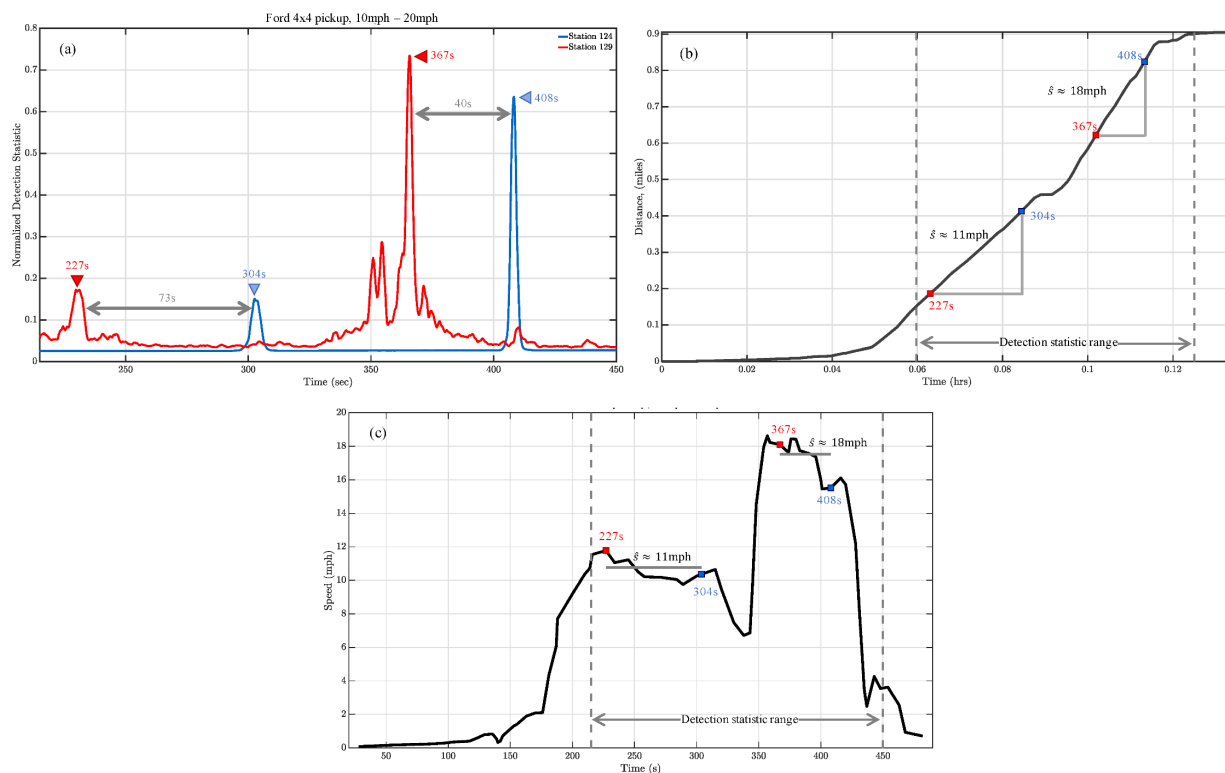

Figure 8: Seismic analysis summary to detect and estimate the speed of a Ford 4x4 pickup truck (hereon called "pickup") using seismic sensors. This example shows records from stations 124 and 129 among 10 available sensors, over a truncated time duration. (a) The normalized sum of the post-processed spectral energy along three orthogonal components of motion, for each station. Markers indicate time series peaks at vehicle POCA to each respective sensor, and arrows indicate their temporal separation. (b) The black

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curve shows the distance the pickup traveled during this particular experiment as miles (vertical axis) versus time in hours (horizontal axis). The markers are associated with the detection times in (a). The solid gray horizontal and vertical lines show measurements of secant line slope and provide two estimates for the vehicle speed between each pair of detection markers, $\hat{s} = 11mph$ and $\hat{s} = 18mph$; dashed vertical lines mark the time axis limits in (a). (c) The thick curve shows the ground truth speed (vertical) of the pickup versus recording time (horizontal axis). Red and blue markers show detection times interpolated onto the curve. The horizontal solid gray curves show the estimates of pickup speed from (b) over the temporal duration between detections. We note that the speed estimates are consistent with the speed of the pickup in each interval. The dashed vertical lines mark the time axis limits in (a).
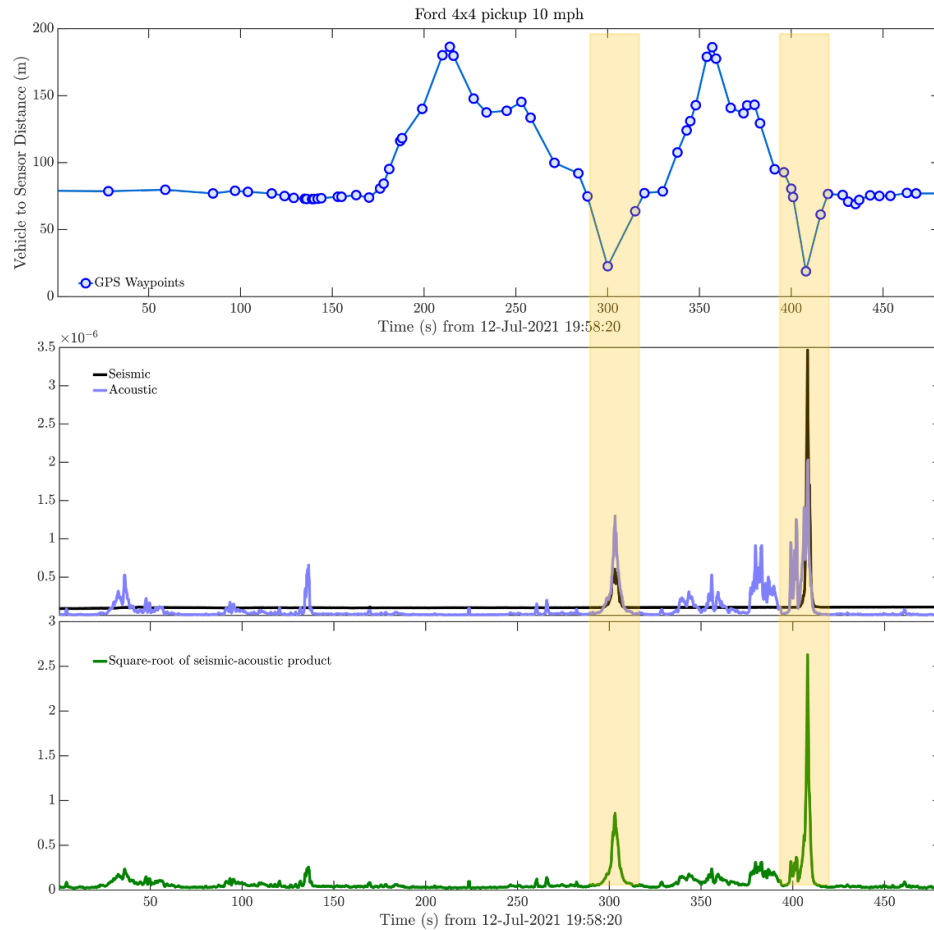

Figure 9. *A summary of seismic and acoustic signature integrated energy records for sensor 124 that recorded a ground-based vehicle (Ford 4x4 pickup) traveling up to 10mph around the track shown in Figure 2. The top plot illustrates the distance of the truck from sensor 124. The middle plot superimposes the integrated three channel seismic energy (black) with the acoustic energy (purple), and shows their coincidence when the truck is at the POCA to sensor 124. The bottom plot shows the square-root of the product of the seismic and acoustic energy (hybrid normalized units not shown on the vertical axis) as a green time series. The yellow highlighted regions indicate that the seismic and acoustic product mutes where the seismic and acoustic data are not temporally coincident, and demonstrates where the sources produce temporally coincident signatures at the POCA.*
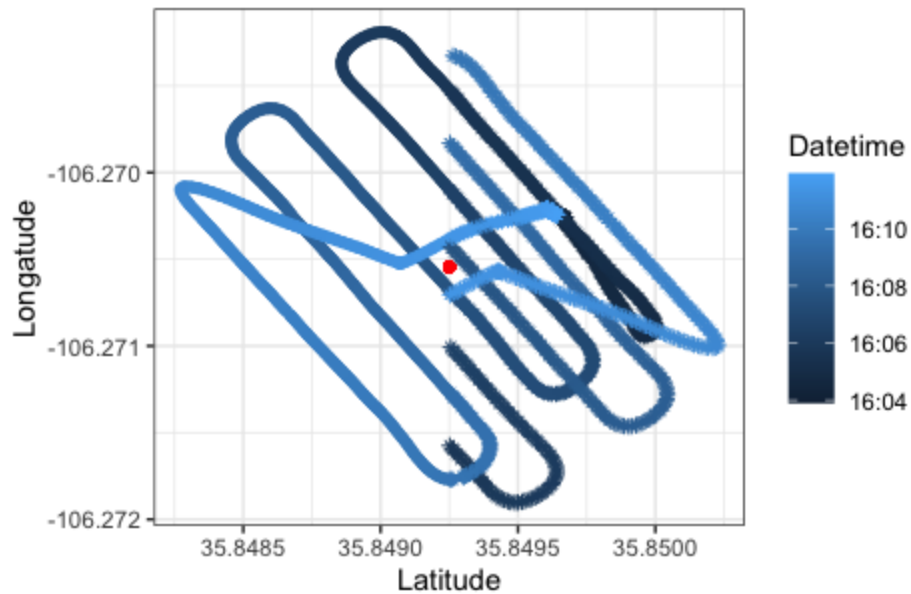
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Figure 10. *Prediction of UAV location using the GPS from the UAV flight controller to compute the range and bearing. The filled in circles are the ground truth, the stars are the predicted values, and color corresponds to the time, so points go from dark to light as time passes. There is a corresponding ground truth and prediction for each color. The methodology does not predict to the left of the sensor (red dot). Ten one-step ahead predictions are shown as GIFs and can be viewed here.*

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ACRONYMS AND DEFINITIONS

2-D	two-dimensional
3-D	three-dimensional
cUAS	Counter-UAS
DoE	Design of Experiment
DDSTE	Deputy Directorate for Science, Technology, and Engineering
DLM	dynamic linear model
GIF	graphics interchange format
GPS	Global positioning system
Hz	Hertz
INT	Intelligence
LANL	Los Alamos National Laboratory
LARSA	Los Alamos Rapid-Deployable Seismoacoustic Array
mph	miles per hour
m/s	meters per second
NM	New Mexico
P-J	TA-51 Pinon-Juniper Plot
POCA	point of closest approach
SUV	sport utility vehicle
TA-51	Technical Area 51
TVS	time-varying signatures
TWS	track-while-scan
UAS	Uncrewed aerial system; an aircraft plus one or more payload components
UAV	Uncrewed aerial vehicle; aircraft only
UTV	Utility task vehicle

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